University of Arizona
Department of Planetary Sciences
Lunar and Planetary Laboratory

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"Interiors of the Giant Planets"

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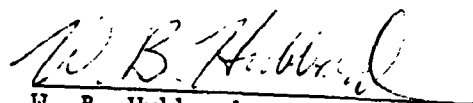
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W. B. Hubbard
Principal Investigator

I. Personnel working on this grant during this reporting period:

Dr. W. B. Hubbard (Principal Investigator, 1/4 time)

Ms. Charlene Lobb (Secretary, 1/4 time)

II. Overview and Summary

Occultation and Geodesy:

Hubbard analyzed data from the Aug. 20, 1985 Neptune occultation, which showed a pronounced central flash. This work was done in collaboration with Meudon Observatory planetary astronomers. A new oblateness and equatorial radius for Neptune was found. The data provide constraints on Neptune's methane abundance at the 0.3-mbar level. A new determination of Neptune's pole position was obtained. A paper on the radius of Ceres was completed, in collaboration with several other groups.

Foreign Travel:

None supported by this grant.

III. Occultations

As stated in the previous report, analysis of the Neptune central flash data obtained from the Aug. 20, 1985 occultation was a principal focus of this reporting period. There were three main objectives of the analysis, which combined the study of the CTIO data with the ESO data obtained by the Meudon group (this was a collaborative effort):
(1) deduce the oblateness, equatorial radius, and pole position angle of Neptune from a combined analysis of the limb-occultation and central-flash data;
(2) determine the temperature/absorption profile in Neptune's atmosphere in the region probed by the occultation data (from 1 μbar to about 0.2 mbar), as well as atmospheric distortions produced by waves or turbulence;
(3) search for additional Neptune ring arcs.

All of the above program was well advanced by the end of this reporting period, with a paper on topic (1) prepared and submitted for publication. Here is a summary of the principal results obtained for each of these topics:

(1) The 8/20/85 data provided measurements of the immersion and emersion occultation profiles at six stations, two in the earth's southern hemisphere and four in the northern hemisphere. We fitted to the immersion/emersion

timings to obtain the limb profile at a pressure level of 1 μbar, and simultaneously fitted to the CTIO and ESO central flash intensity data. Results of this analysis are presented in Table 1.

The parameters were e, the scale height at the level probed by the central flash H_f (the ratio of H_f to the true scale height at the central flash level is equivalent to the transmission factor), the coordinates x_0, y_0 of the projected geometrical center of Neptune in the sky plane, and the projected position angle of Neptune's north pole in the sky plane, p_n. The model was also dependent on the equatorial radius of Neptune a_0, the Neptune-centered declination of the earth, β_e, and the scale height at the immersion/emersion level, H_0. The fitting procedure does not provide a meaningful constraint on β_e, which must be derived from independent information.

The inferred scale height at the flash level H_f corresponds to a temperature of about 100 K at a pressure of 0.24 mbar. If the actual temperature at this level is higher, then the transmission is reduced from unity by the ratio of the inferred to actual temperatures. At the half-intensity points on the limb, the region probed by the rays has a scale height H_0 of 52 km (average of results from ESO and CTIO), corresponding to a temperature of 153 K for solar-composition gas. The corresponding pressure is 1.0 μbar. Table 1 presents the oblateness e at this level in the atmosphere. In the fitting procedure, allowance is made for the variation of e with depth. We estimate the altitude difference between the 1-μbar level and the 0.24-mbar level to be approximately 285 km, or 0.011 in units of a_0. If we let

$$\eta = \frac{d \ln e}{d \ln \beta}, \tag{1}$$

where β is the radius in units of a_0, then the surface value of η is given by hydrostatic-equilibrium theory (Zharkov & Trubitsyn 1978), assuming a constant rotation rate:

$$\eta = 3 - \frac{15}{2} \frac{J_2}{e} \tag{2}$$

where J_2 is the second-degree zonal harmonic of Neptune's gravity field. Employing eq. (2), we find the oblateness at the flash level $e_f = 0.983$ e, where e is the oblateness at the 1-μbar level. The intensity pattern in the central flash is computed using e_f. The corrections x_0, y_0 to the relative positions of Neptune and the occulted star show that the ephemeris position of Neptune must be moved to the west and south (assuming no correction to the predicted star position).

Using the nominal Neptune pole position at the time of the occultation, computed from Harris' (1984) paper, we obtain $p_n = 22.9°$ and $\beta_e = -25.0°$. This position assumes that the angle ϵ between Neptune's rotation vector and the angular momentum vector of the Neptune-Triton system is $-3.6°$. If ϵ is taken to be zero, corresponding to negligible Triton mass, then Harris' ephemeris gives $p_n = 21.6°$, $\beta_e = -21.7°$. According to the results given in Table 1, the best-fit value of p_n from solution 1 is 20.9°. This result is within one probable error of the Harris' pole

position for zero Triton mass, but cannot be regarded as strong support for this interpretation as opposed to the one for a nominal Triton mass, since we have no constraint on $\beta_\bullet$. We use the value of $\beta_\bullet$ corresponding to the nominal Harris ephemeris, i.e. $\beta_\bullet = -25.0°$, although the value of p_n is adjusted to fit the central flash intensities and times observed at ESO and CTIO. The value of e given in Table 1 thus corresponds to $\beta_\bullet = -25.0°$. To within errors of order e^2, the inferred oblateness scales as $(\cos \beta_\bullet)^{-2}$. Thus if $\beta_\bullet$ were revised to $-21.7°$ from $-25.0°$, values of e which we derive would have to be reduced by five percent.

The value of a_0 given in Table 1 includes a correction of 100 km for refractive and general-relativistic bending of the rays (Hubbard et al., 1985).

TABLE 1. Parameters of general solution

$$H_f = 35 \text{ km} \quad (H_0 = 52 \text{ km})$$
$$e \ (1 \ \mu\text{bar}) = 0.0204 \pm 0.0014$$
$$x_0 = -25715.27 \text{ km}$$
$$y_0 = -6117.32 \text{ km}$$
$$p_n = 20.9°$$
$$a_0 \ (1 \ \mu\text{bar}) = 25260 \pm 10 \text{ km}$$

Is Neptune far less centrally-condensed than Uranus? Let us review this question by first computing the second-degree response coefficient Λ_2 for Uranus. This quantity is given by

$$\Lambda_2 = J_2/q, \tag{3}$$

where

$$q = \omega^2 a_0^3/GM, \tag{4}$$

ω is the planet's angular rotation velocity (assumed uniform), G is the gravitational constant, and M is the planet's mass. In eq. (3), the second-degree zonal harmonic J_2 is normalized to a_0. Eq. (3) is valid to order q^2.

For Uranus we use $J_2 = 3.352 \times 10^{-3}$ (Elliot 1982). For a rotation period of 16.31^h, we would have $q = 0.0355$, but the recent Voyager 2 measurement of the rotation rate of the deep Uranian interior gives a rotation period of 17.24^h (Warwick et al., 1986), which implies $q = 0.0318$, and thus $\Lambda_2 = 0.105$ for Uranus.

For Neptune we employ the equation

$$\Lambda_2^{-1} - \frac{2e}{J_2} - 3. \tag{5}$$

Taking Harris' lower bound for J_2 and our upper bound for e, we obtain $\Lambda_2 - 0.114$, and thus $q - 0.0325$ and the rotation period $P - 14.8^h$. If we take Harris' upper bound for J_2 and our lower bound for e, we obtain $\Lambda_2 - 0.171$, $q - 0.0251$, $P - 16.9^h$.

We conclude that despite improved error bars on Neptune's oblateness, there is still substantial uncertainty in its degree of central condensation as measured by Λ_2. There is evidence that Neptune is less centrally-condensed than Uranus, but a definitive resolution of this matter must await a determination of the rotation period of Neptune's deep interior, as would be provided by a measurement of the rotation period of a magnetosphere. When significant differential rotation is present in a planetary atmosphere, as is apparently the case for Uranus, the oblateness may differ substantially from that corresponding to uniform rotation, for a fixed value of J_2 (Hubbard, 1986). This may explain the substantial discrepancy between the Voyager value for Uranus' deep rotation period and the value derived by Elliot (1982) on the basis of an occultation measurement of the oblateness, $P - 15.5^h \pm 1.3^h$. It may also account for the discrepancy between the rotation period for Neptune which we obtain, $P - 15.9^h \pm 1.0^h$, and the rotation period of 18.2^h proposed by Belton et al. (1981).

(2) A paper on the interpretation of the 8/20/85 Neptune central flash data has been prepared and submitted to Nature (Lellouch et al., 1986). Fitting to the central flash data alone gives $e - (2.08 \pm 0.19) \times 10^{-2}$, in good agreement with the solution given in Table 1, and, assuming a stratospheric temperature of 120 K at 0.3 mbar, an atmospheric transmission of 0.70 ± 0.20 for an integrated column density of 1.9 km-atm. The opacity at the central flash level is attributed to CH_4 absorption, and the inferred value for the CH_4 mixing ratio is 0.6% with a factor 10 uncertainty. This may indicate supersaturation of methane in Neptune's atmosphere. However, if the atmospheric temperature is 100 K at the 0.23-mbar level, the central flash intensity level is entirely explained and there is no significant opacity.

(3) The 8/20/85 occultation at CTIO did not reveal any Neptune ring arcs, although one was detected in Hawaii. This result is consistent with the emerging picture of these features, according to which they have typical azimuthal lengths which do not exceed 10^3 km.

A major paper on the profile of Ceres was submitted to *Icarus* during this reporting period (see Papers Submitted). This represents the outcome of analysis of data from 13 sites for the occultation of a star by Ceres on 13 November 1984, to which we contributed data from 3 sites. The analysis gives an equatorial radius for Ceres of 479.6 ± 2.4 km and a polar radius of 453.4 ± 4.5 km. These results will provide a fundamental calibration of the asteroid size scale.

IV. Publications and presentations during this reporting period

(a) Published papers:

JHK Photometry of Candidate Stars for Occultation by Neptune, by F. Vilas and D. J. Mink, *PASP* **98**, 116-117, 1986

Occultation detection of a Neptunian ringlike arc, by W. B. Hubbard, A. Brahic, B. Sicardy, L.-R. Elicer, F. Roques, and F. Vilas, *Nature* **319**, 636-640, 1986.

1981N1: A Neptune Arc?, by W. B. Hubbard, *Science* **231**, 1276-1278, 1986.

(b) Papers submitted for publication:

Evolution of Super-Jupiters, submitted December 1985 for publication in proceedings of "Astrophysics of Brown Dwarfs", conference at George Mason University, October 14-15, 1985.

The phase diagram of hydrogen with other elements, and applications to Jovian planet interiors. Submitted to Proceedings of NATO Advanced Study Institute, Newcastle upon Tyne, England, 1985.

The 1985 August 20 occultation by Neptune: The central flash determination of Neptune's oblateness and methane stratospheric mixing ratio, by E. Lellouch, W. B. Hubbard, B. Sicardy, F. Vilas, and P. Bouchet, submitted to *Nature*.

The size, shape, density, and albedo of Ceres from its occultation of BD+8°471, by 37 authors (Millis *et al.*), including W. B. Hubbard, submitted to *Icarus*.

(c) External presentations:

Evolution of Super-Jupiters, by W. B. Hubbard, "Astrophysics of Brown Dwarfs" conference at George Mason University, October 14-15, 1985.

VII. Financial Status

Expenditures are on schedule.